INFUSION AND POLYMERIZATION OF THICK GLASS/ELIUM® ACRYLIC THERMOPLASTIC RESIN COMPOSITES

ZEBRA PROJECT
Zero wastE Blade ReseArch

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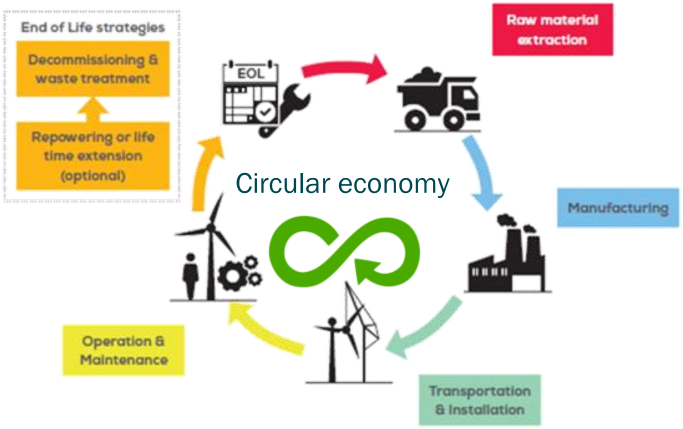
2 August 2023

ZEBRA: Zero wastE Blade ReseArch project

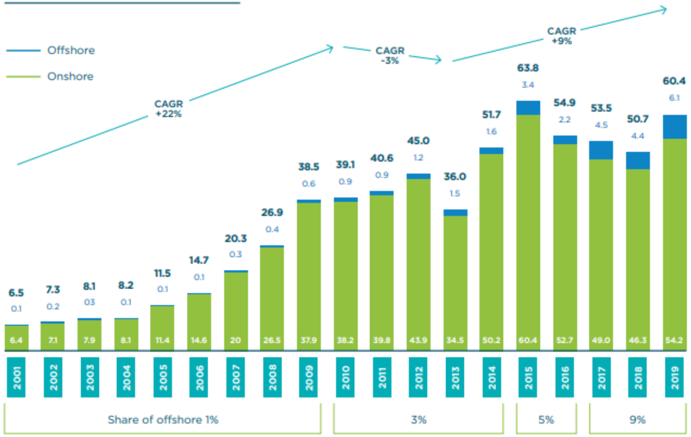
Circular economy

The life cycle of a wind turbine



Source: Accelerating wind turbine blade circularity, Wind Europe

The global rate of Wind turbine installations



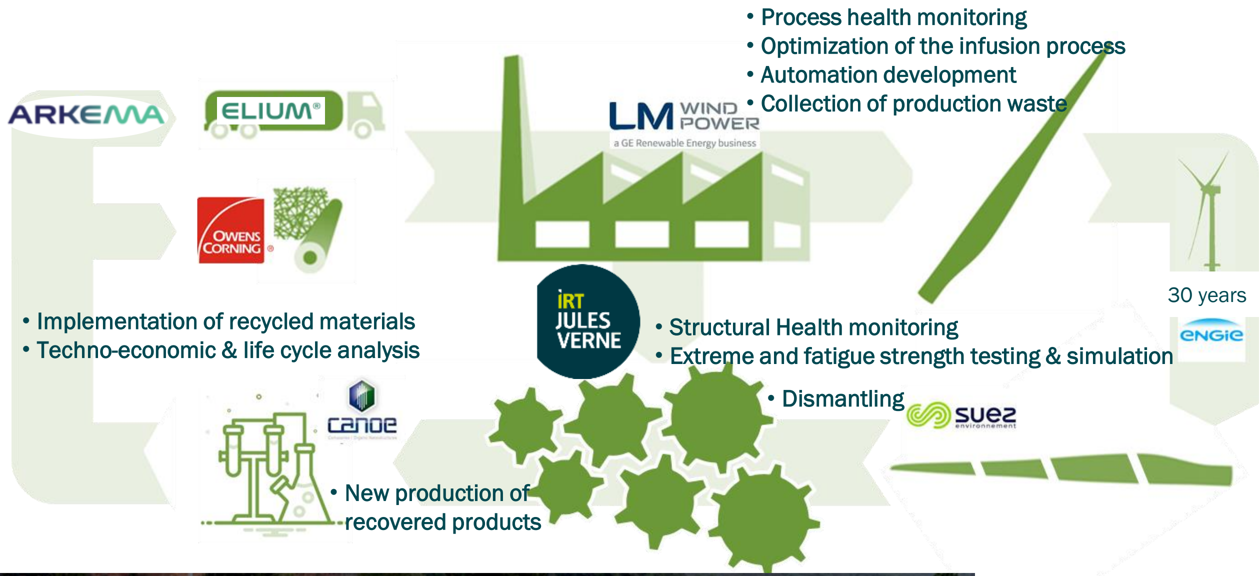
Source: Sustainable decommissioning: wind turbine blade recycling

Examples of blade repurposing

ZEBRA project: Zero wastE Blade ReseArch

Project objectives

Accelerate the industry transition to a circular economy by designing and manufacturing the first 100% recyclable wind blades, using the thermoplastic resin ELIUM®, developed by Arkema.

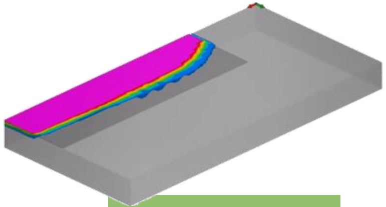


The 62m blade manufactured by LM Wind Power using Arkema's Elium® resin, Ponferrada, Spain, March 2022.

ZEBRA project: IRT Jules Verne activities

Manufacturing

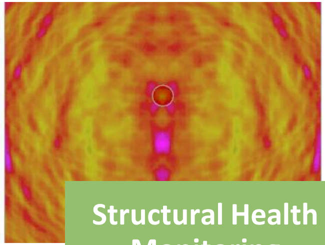
Process Health Monitoring



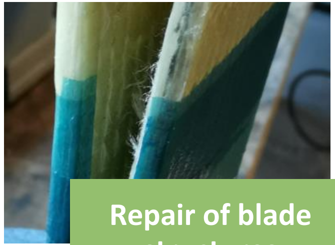
Modeling and Simulation

Mechanical testing and simulation

Automation development



Structural Health Monitoring



Repair of blade structures

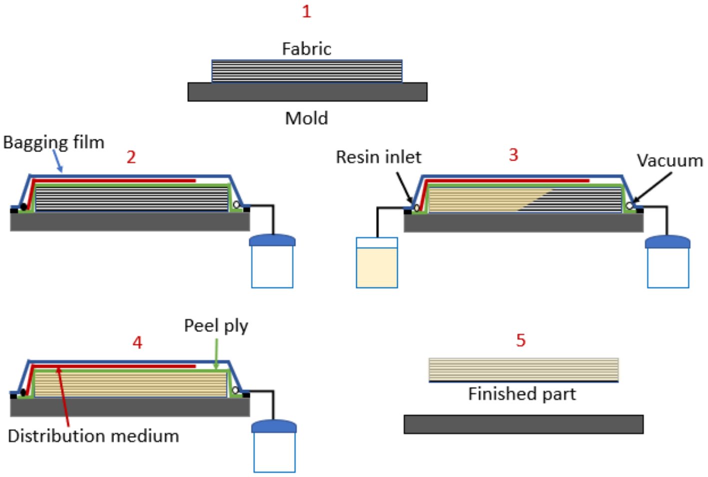
Recycling/techni co-eco analysis

Modeling and simulation of the infusion process

Context

Study objectives

- Establish physics-based simulations
  - Evaluate the model accuracy with experiments
  - Predict the process behavior for thick and complex parts



Liquid resin infusion process (LRI)

Material characterization

- Parameter/model identification and modeling

Experimental validation

- Validation of simulation results and assumptions
- Infusion simulations of growing complexity

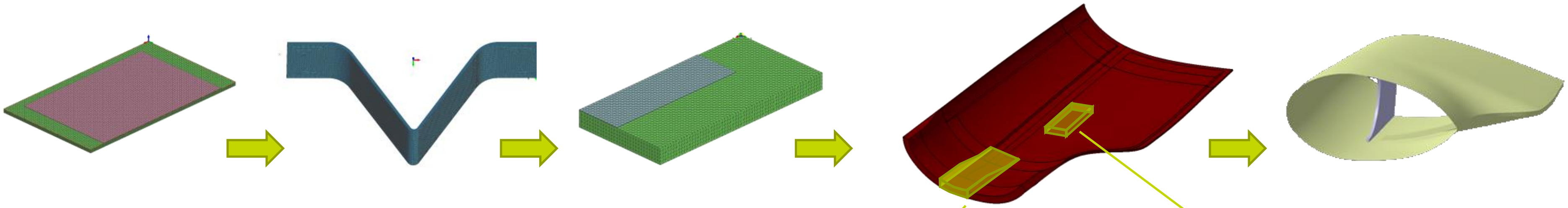
Decision support

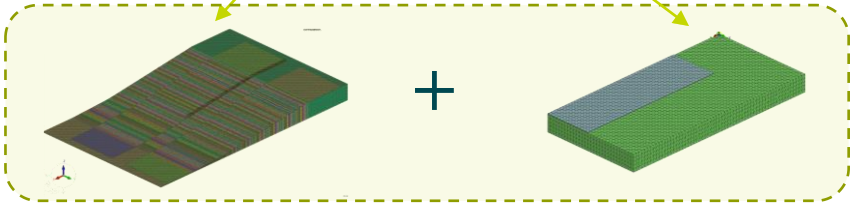
- Prediction for new parts

Modeling and simulation of the infusion process

Simulation strategy: parts with growing complexity

Thin parts	Technological part	Thick parts	Ply drop-off	Wind blade root
2D/3D	2D/3D	3D	3D	2D/3D





Heat transfer
Resin polymerization
Permeability measurement
Infusion strategy
Effect of gravity

Thickness variation
Effect of the distribution medium
Transverse flow
Effect of ply drop-off
Geometrical non-linearities

Modeling and simulation of the infusion process

Simulation strategy

- Permeability of preform and flow medium
- Compression behaviour
- Resin viscosity and surface properties
- DSC tests, polymerization model and parameter identification

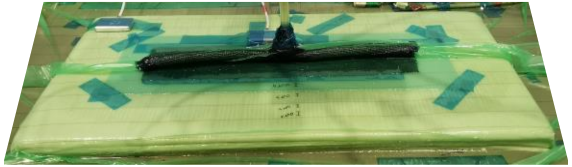
Material characterization & parameter identification

- Simplifications
- Assumptions

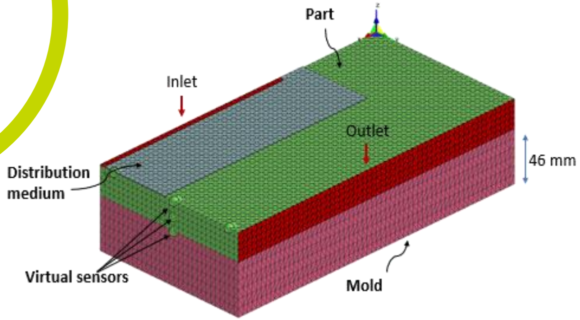
Modeling assumptions

Simulation

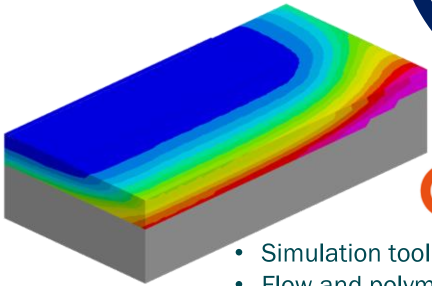
Infusion experiments & monitoring



- Repeatability experiments
- Data acquisition



Validation

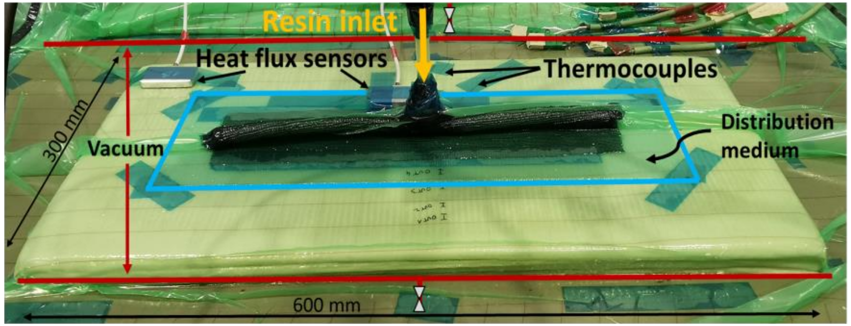


- Simulation tool: PAM-RTM©
- Flow and polymerization

- Comparison between simulation and experiments

Infusion tests and process health monitoring

Process Health Monitoring



OPC UA communication protocol

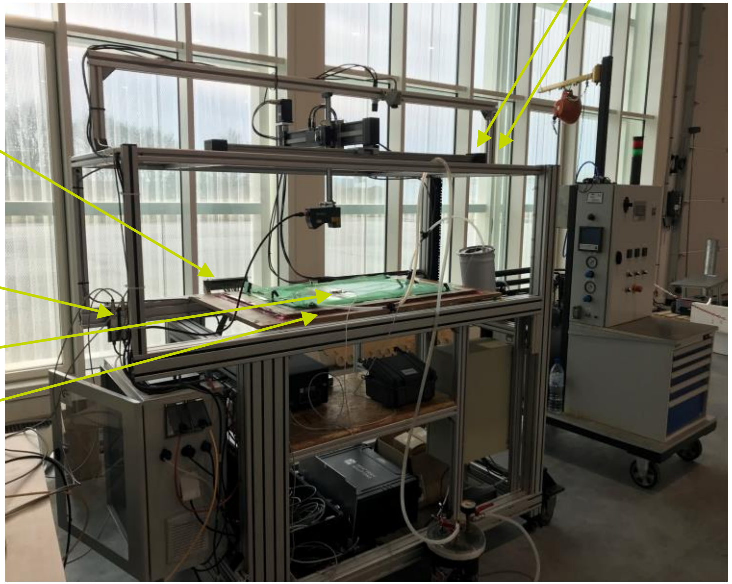
Vis/IR cameras

Thermocouple

Pressure sensors

Heat Flux

Dielectric sensors



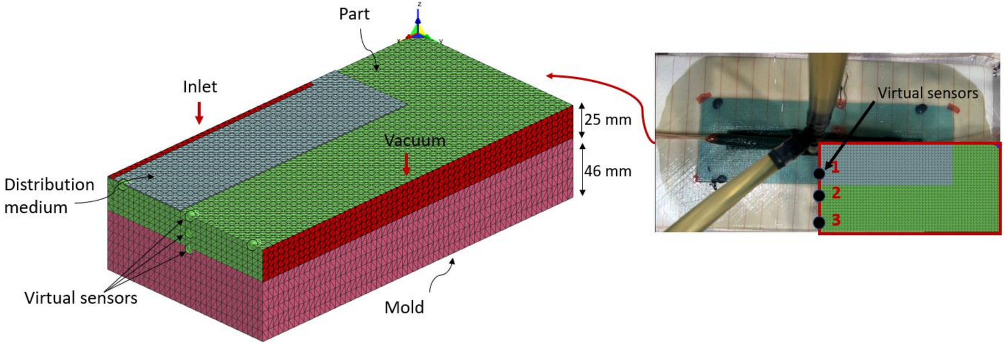
Process Health Monitoring

Infusion test bench

- Evaluate sensors dedicated to control infusion process
- Part/mold/vacuum bag embedded sensors/conrtol without contact

Modeling and process simulation

Process physics



Experiment	Infusion A	Infusion B
Part thickness (mm)	25	25
Initial viscosity (Pa.s)	0.094	0.122
Initial temperature (°C)	24.8	19.6

Flow in porous media

Continuity equation $div(\vec{V}) = 0$

Darcy's law $\vec{V} = \frac{-\boldsymbol{K}}{\mu}\nabla P$

Heat transfer

$$\rho\, c_p \frac{\partial T}{\partial t} + \rho_r c_{p,r} \vec{V}.\nabla T = -\nabla.(\lambda.\nabla T) + \dot{R}$$

Polymerization kinetics

$$\dot{R} = \rho_r \Delta H \frac{\partial \alpha}{\partial t} \qquad \frac{\partial \alpha}{\partial t} = f(t, \alpha)$$

$\dot{R}$: source term related to polymerization

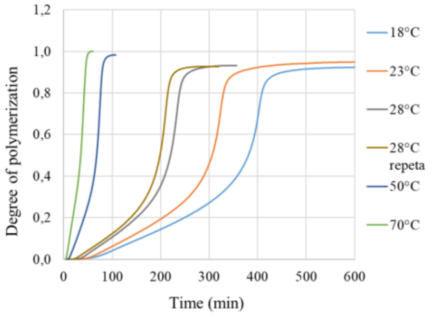
Material chracterization

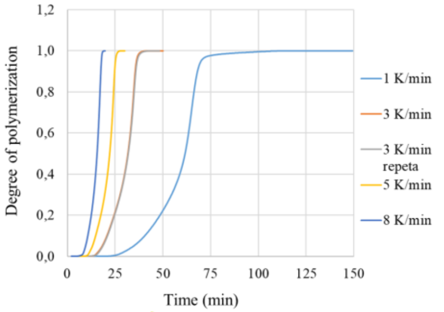
Differential scanning calorimetry (DSC) tests

DSC scans

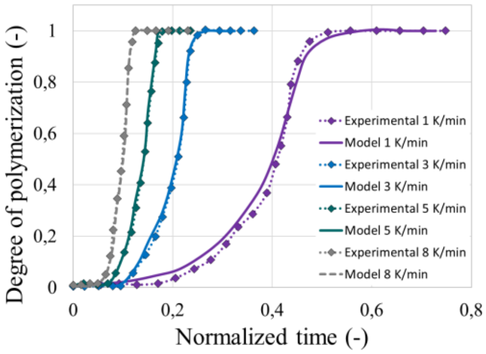
Thermal Analysis DSC Q200

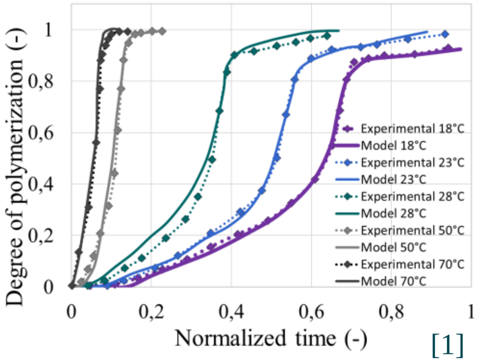
- Isothermal and dynamic DSC scans
- Elium® 190 XO/SA mixture





Identification





[1]

Semi-empirical Arrhenius-type autocatalytic model

$$\frac{d\alpha}{dt} = A_1 exp\left(\frac{-E_1}{RT}\right)(1-\alpha)^{n_1} + A_2 exp\left(\frac{-E_2}{RT}\right)\alpha^{n_2}(\alpha_{max}-\alpha)^{n_3} \quad [2]$$

[1] Y. Denis et al. , ESAFORM, Kraków, Poland, 2023
[2] N. Han et al., "Experimental and computational analysis of the polymerization overheating in thick glass/Elium® acrylic thermoplastic resin composites," *Compos B Eng*, vol. 202, p. 108430, 2020.

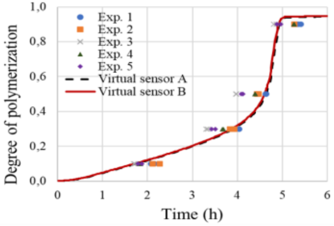
CAPACITÉS

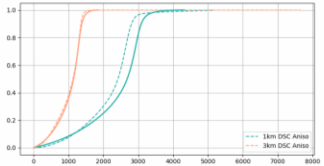
Modeling and process simulation

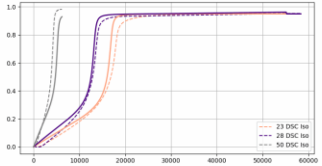
Polymerization kinetics model

Validation and implementation

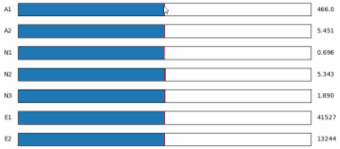
Comparison with experiments







- Sensitivity analysis
- Validation of the curing model with FreeFem



Implementation into PAM-RTM

- Experimental DSC curves fitting to a semi-empirical Arrhenius-type autocatalytic model
- Model parameters identified and used as input to PAM-RTM© simulations
- Implementation on Python, FreeFem and ESI© Pam-RTM

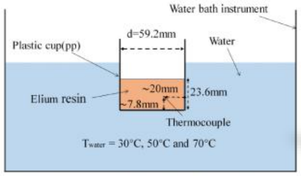
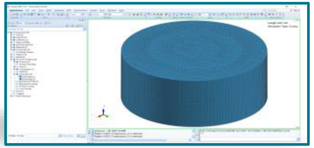
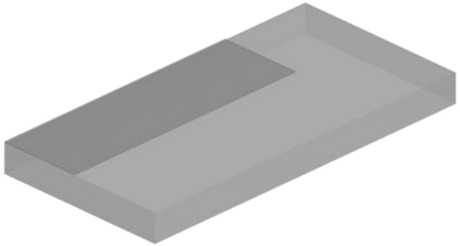


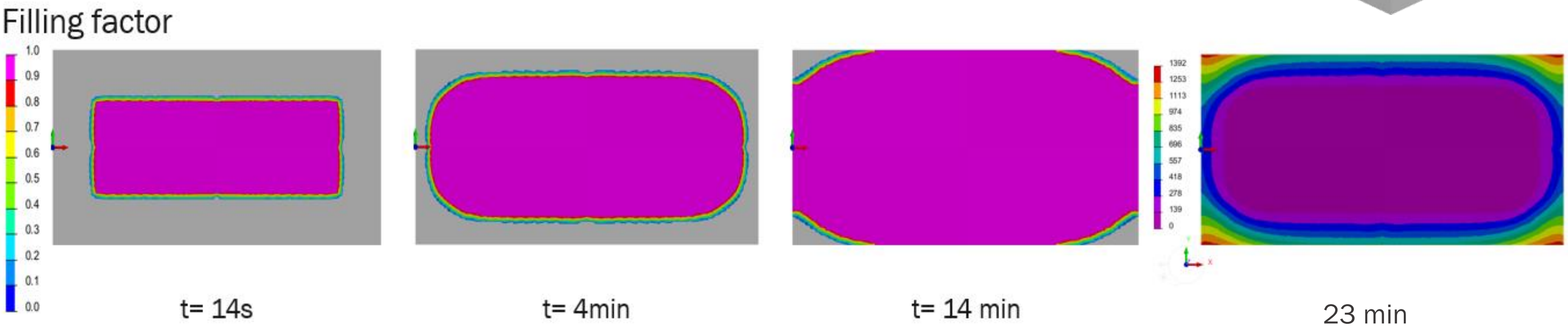
Fig. 2. A schematic view of the water bath experiments together with the dimensions and the thermocouple location.

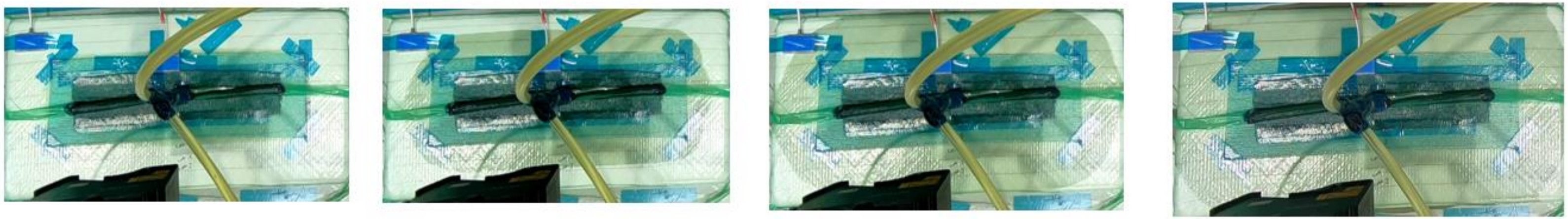


Modeling and process simulation

Validation with experiments: flow front position





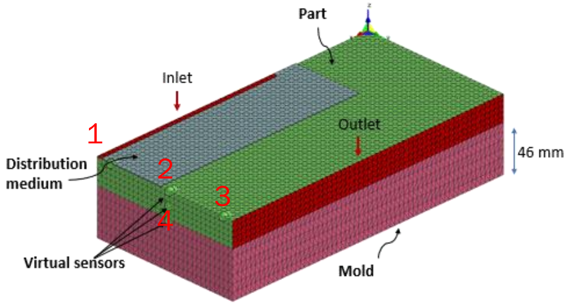


- Good agreement between flow simulations and experiments in the in-plane directions
- Perspective: validation with infusion tests and flow prediction through the part thickness

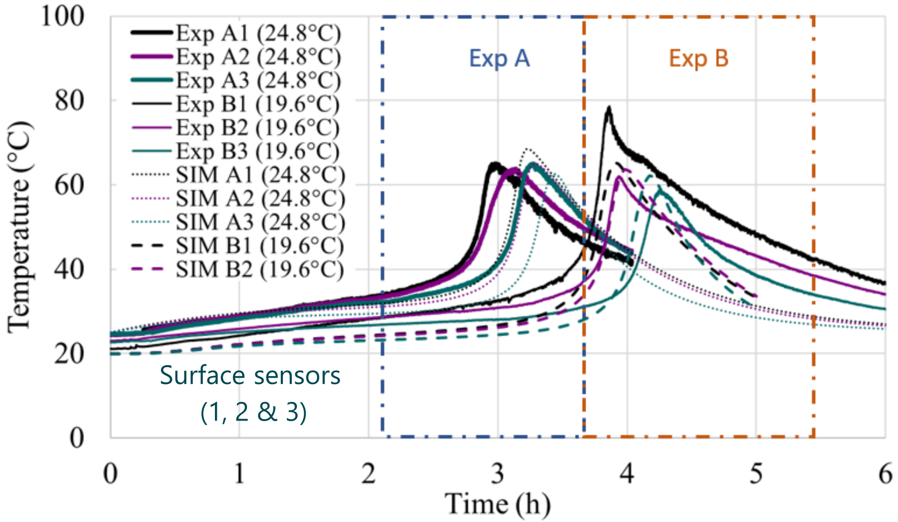
Modeling and process simulation

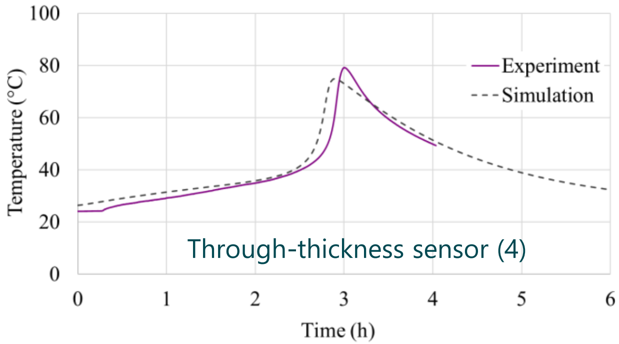
Validation with experiments: resin polymerization

- Comparison between A and B experiments and simulation
- Virtual sensors placed at the part surface 1, 2 and 3 at the same positions
- Deviations at the part surface/good agreement through the thickness



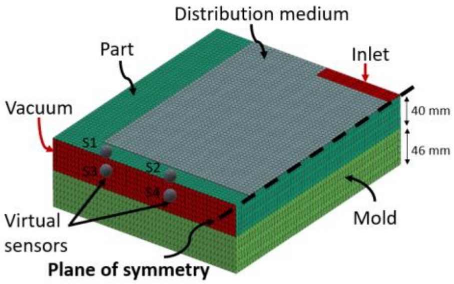
Experiment Number	Infusion A	Infusion B
Initial temperature (°C)	24.8	19.6
Peak temperature (°C)	≈65	≈60
Time to peak	2h58min	3h52min

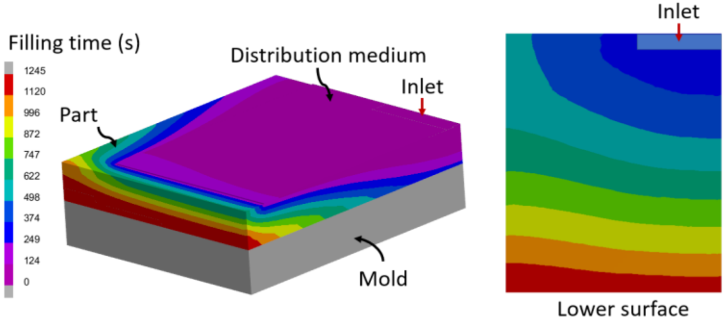


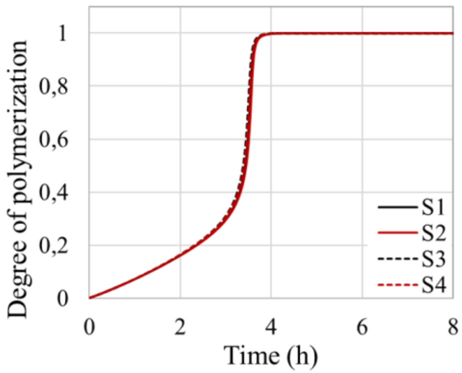


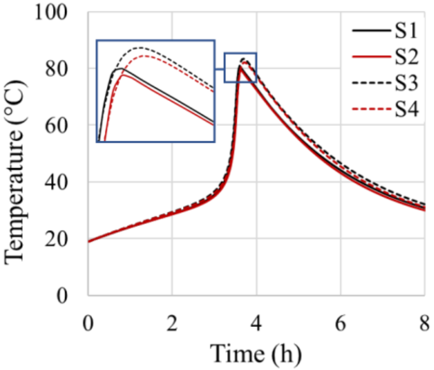
Modeling and simulation

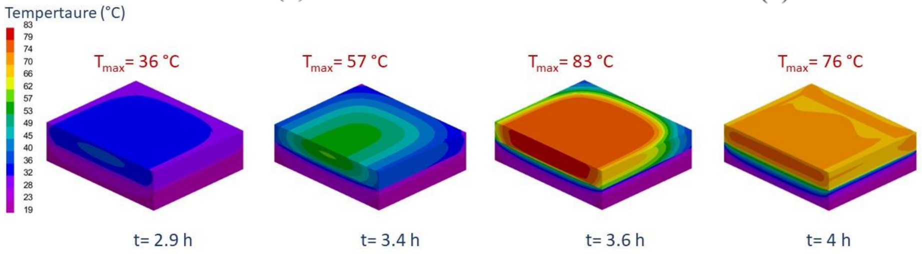
Predictions for a 40 mm thick part

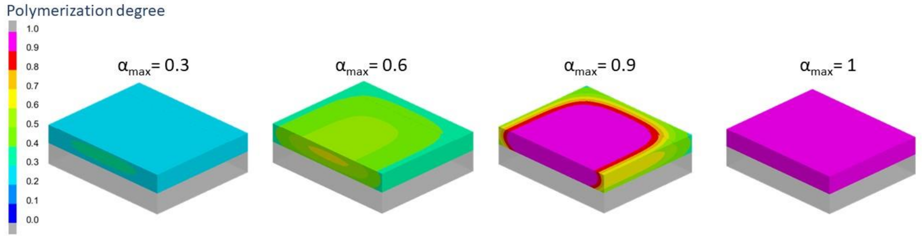










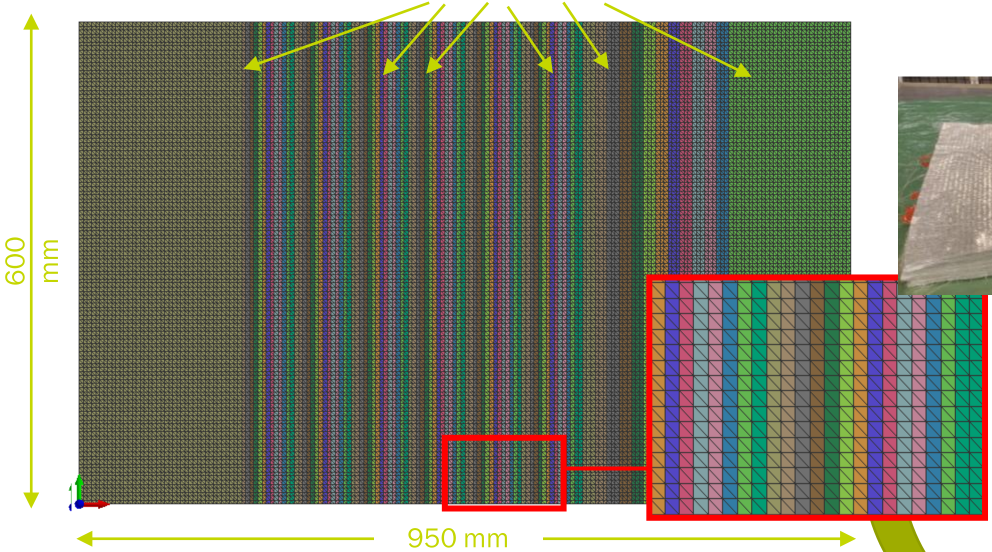


Thick lay-up with ply drop-off

Material assignment

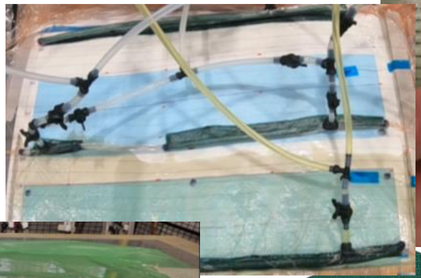
Objective: thicker part (65.5 mm) with new geometrical complexity

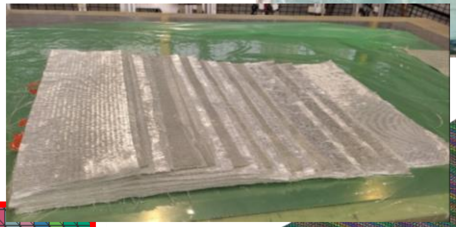
Regions of different stacking

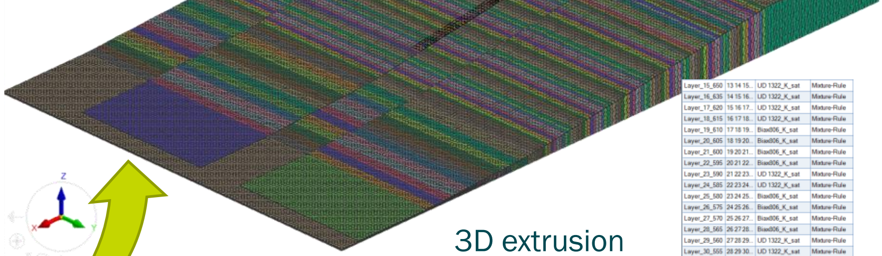


- Automatization of material assignment

Part infusion





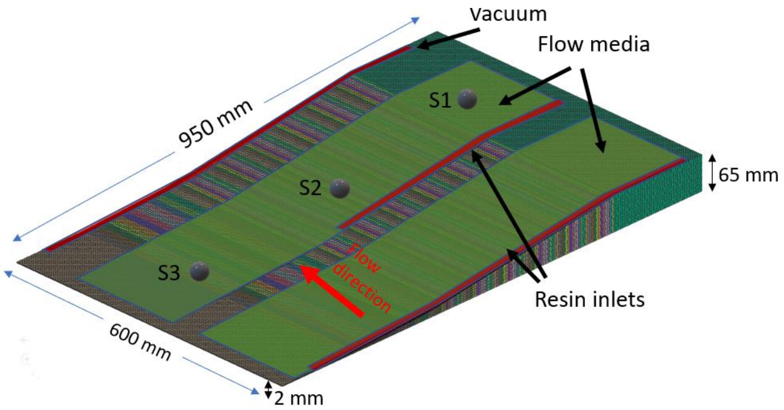


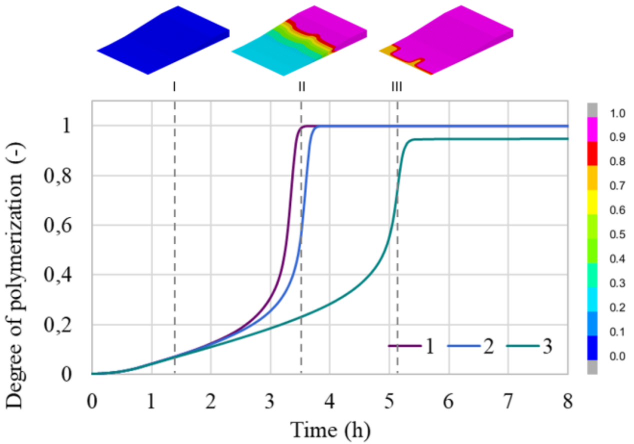
3D extrusion

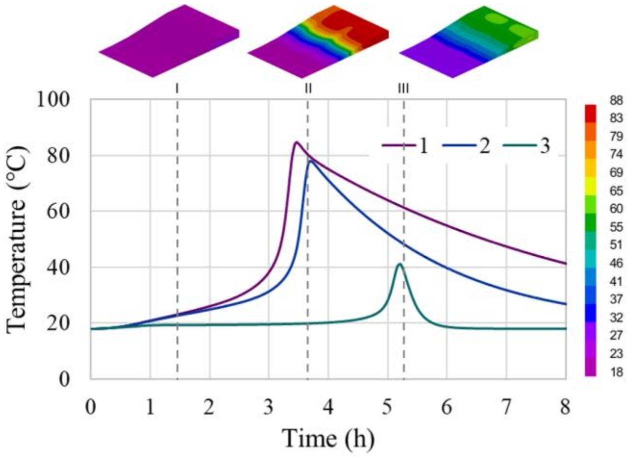
Layer_15_650	13 14 15...	UD 1322_K_sat	Mixture-Rule
Layer_16_635	14 15 16...	UD 1322_K_sat	Mixture-Rule
Layer_17_620	15 16 17...	UD 1322_K_sat	Mixture-Rule
Layer_18_615	16 17 18...	UD 1322_K_sat	Mixture-Rule
Layer_19_610	17 18 19...	Biax806_K_sat	Mixture-Rule
Layer_20_605	18 19 20...	Biax806_K_sat	Mixture-Rule
Layer_21_600	19 20 21...	Biax806_K_sat	Mixture-Rule
Layer_22_595	20 21 22...	Biax806_K_sat	Mixture-Rule
Layer_23_590	21 22 23...	UD 1322_K_sat	Mixture-Rule
Layer_24_585	22 23 24...	UD 1322_K_sat	Mixture-Rule
Layer_25_580	23 24 25...	Biax806_K_sat	Mixture-Rule
Layer_26_575	24 25 26...	Biax806_K_sat	Mixture-Rule
Layer_27_570	25 26 27...	Biax806_K_sat	Mixture-Rule
Layer_28_565	26 27 28...	Biax806_K_sat	Mixture-Rule
Layer_29_560	27 28 29...	UD 1322_K_sat	Mixture-Rule
Layer_30_555	28 29 30...	UD 1322_K_sat	Mixture-Rule
Layer_31_550	29 30 31...	Biax806_K_sat	Mixture-Rule
Layer_32_545	30 31 32...	Biax806_K_sat	Mixture-Rule
Layer_33_540	31 32 33...	Biax806_K_sat	Mixture-Rule

Predictions for thick parts

Polymerization behaviour in drop-off parts

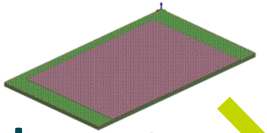






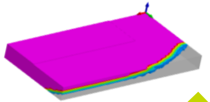
- Illustration of a portion of a wind blade root
- Evolution of thickness from 65 mm (101 plies) to 2 mm (4 plies)
- Three sensors located at the part surface at 65 mm (1), 40 mm (2) and 2 mm (3)

Accomplished work and perspectives



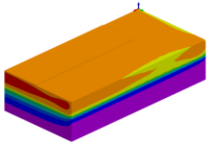
Simple parts

Experimental validation, permeability measurement, process monitoring, sensor testing and model adjustment.



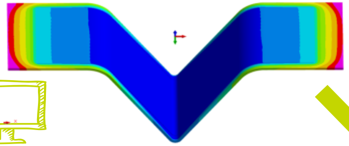
Thick parts

Correlation of the in-plane flow with experiments for thick parts. Polymerization kinetics and exothermic reaction.



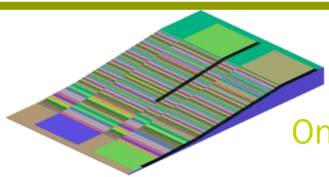
Mold simulation

Modeling the flow and polymerization considering the mold, assigning the mold materials and parameters and studying the influence on the resin kinetics.



Technological part

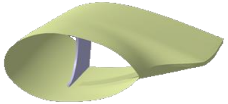
Modeling the infusion process, correlation with experimental acquisitions, influence of gravity and optimization of the infusion scenario.



Ongoing

Thick parts with drop-off

Flow and polymerization simulations for thick parts and zones of ply drop-off. Comparison with experiments, implementation of defects (race-tracking), prediction and process optimization.



Wind blade root

Simulation of a complex part by implementing the hypotheses taken from previously studied cases.

This study is a part of the ZEBRA project led by IRT Jules Verne (French Institute of Research and Technology in Advanced Manufacturing). The authors wish to thank the industrial partners of this project: LM Wind Power, Arkema, Owens Corning, ENGIE, Suez and CANOE, and the Research Institute in Civil and Mechanical Engineering (GeM), Ecole Centrale de Nantes, Nantes University.

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